# ARE THE OGLE MICROLENSES IN THE GALACTIC BAR?

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## ABSTRACT

The analysis of the first two years of OGLE data revealed 9 microlensing events of the galactic bulge stars, with the characteristic time scales in the range $8.6 < t_0 < 62$ days, where $t_0 = R_E/V$. The optical depth to microlensing is larger than $(3.3 \pm 1.2) \times 10^{-6}$, in excess of current theoretical estimates, indicating a much higher efficiency for microlensing by either bulge or disk lenses. We argue that the lenses are likely to be ordinary stars in the galactic bar, which has its long axis elongated towards us. A relation between $t_0$ and the lens masses remains unknown until a quantitative model of bar microlensing becomes available. At this time we have no evidence that the OGLE events are related to dark matter.

The geometry of lens distribution can be determined observationally when the microlensing rate is measured over a larger range of galactic longitudes, like $-10^o < l < +10^o$, and the relative proper motions of the galactic bulge (bar) stars are measured with the HST.

*Subject headings:* cosmology: dark matter – galaxy: center – galaxy: structure – gravitational lensing – stars: low mass, brown dwarfs

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## 1. INTRODUCTION

The OGLE project (Optical Gravitational Lensing Experiment) was described by Udalski et al. (1992), and the lensing events were reported by Udalski et al. (1993, 1994a,b). All observations were done with the 1 meter Swope telescope at the Las Campanas Observatory, operated by the Carnegie Institution of Washington. The detector was a single Loral CCD with $(2k)^2$ pixels. We used a somewhat modified DoPhot photometric software (Schechter, Mateo & Saha 1993) to extract stellar magnitudes from the CCD frames. All technical details were provided in Udalski et al. (1992, 1994b) and references therein. The location of all 9 OGLE events in the color-magnitude diagram is shown in Fig. 1.

The first estimate of the optical depth to gravitational microlensing of the galactic bulge stars as observed by the OGLE has recently been published (Udalski et al. 1994b). The result is surprising: the minimum optical depth is estimated to be $\sim (3.3 \pm 1.2) \times 10^{-6}$ in Baade's Window and the nearby galactic bar fields. Theoretical models predicted a much lower value, somewhere in the range of $0.5 - 1.0 \times 10^{-6}$ (Paczyński 1991; Griest et al. 1991; Kiraga and Paczyński 1994, hereinafter referred to as KP; Giudice et al. 1994). The aim of this paper is to discuss this apparent discrepancy and to propose a simple observational test that could definitely locate the apparent excess of lensing masses either in the disk or in the bulge. Future observations will resolve this uncertainty. Here, we adopt the OGLE estimate as correct, and we follow the consequences. It is important to note that a similar (high) estimate of the optical depth to the galactic bulge stars has been recently obtained by the MACHO collaboration (Alcock et al. 1994).

The 9 OGLE events satisfied a variety of distribution tests expected of gravitational microlensing (Udalski et al. 1994b), but we cannot claim that we have proven beyond any reasonable doubt that they are indeed due to lensing. Nevertheless, the case for lensing is strong, as no other kind of intrinsically variable stars of this type is known. The lensed objects are scattered over a large region of the color-magnitude diagram, in proportion to the number density of the observed stars as apparent in Fig. 1 and quantitatively assessed by Udalski et al. (1994b). In this large region of the diagram, covering roughly solar type stars at the main sequence turn-off point and red subgiants up to the "red clump", no intrinsically variable stars are know, at least not with amplitudes as large as our lens candidates. Therefore, throughout this paper we assume that the 9 OGLE events were due to gravitational microlensing. We adopt the traditional definition of the event time scale: $t_0 = R_E/V$ (Paczyński 1986), where $R_E$ is the Einstein ring radius, and $V$ is the relative velocity of the source, lens, and observer.

## 2. MODELS

We follow KP in our model of the galactic disk and the galactic bulge contribution to the lensing. We ignore the possible contribution of the dark galactic halo as the OGLE was aimed at the event time scale characteristic of ordinary stellar masses rather than very low or very high mass dark objects. In any case, the optical depth in the direction of Baade's Window due to halo objects of any kind is only $\sim 0.13 \times 10^{-6}$ (Griest et al. 1991), much less than the contribution due to any disk or bulge models.

It is a convenient coincidence that while looking at the galactic latitude $|b| = 4^o$ the radial and the vertical disk exponentials (Bahcall 1986) almost exactly cancel each other if the galactic longitude is small, $|l| < 20^o$ or so, which is the case for all our fields (cf. Paczyński 1991, Udalski et al. 1994b). This implies that the number density of stars is expected to be approximately constant along the line of sight. However, this conventional model is in apparent conflict with the observations.

First, the recent measurements of the disk scale height by Kent et al. (1991) indicate that the scale height decreases towards the galactic center, which implies that the number density of disk stars as seen through Baade's Window should gradually decrease with the distance from observer. Second, preliminary analysis of the color − magnitude diagrams obtained with the OGLE revealed an unexpected feature in the distribution of disk stars (Paczyński et al. 1994): the density is *observed* to be uniform out to some distance $d_{max} \approx 3 - 4\ kpc$ but it decreases by a large factor beyond $d_{max}$, as if the disk was nearly empty within radius $r_{in} = R_0 - d_{max}$, where $R_0$ is our distance from the galactic center. The fact that the inner disk has low density has been noticed before with the OH/IR stars (Baud et al. 1981, Blommaert et al. 1994). Unfortunately, the current knowledge of the density distribution is so limited that for the purpose of this paper we adopt a simple distributions of the stellar density along the line of sight through Baade's Window:

$$\rho(d) = \rho_0 \quad \text{for} \quad d \le d_{max} \ , \qquad \rho(d) = 0 \quad \text{for} \quad d > d_{max}, \tag{1}$$

where $\rho_0$ is the local disk density near the sun.

Following KP we adopt Kent's (1992) bulge model. The lensing is made possible because the bulge has a finite radial extent, with the stars in front lensing those in the back. We adopt the bulge cumulative luminosity function to be a power law with the slope (–2). The results depend only very weakly on this number (KP). The main limitation of the adopted structure is its axial symmetry, while there is plenty of evidence that the bulge is in fact bar-like (cf. de Vaucouleurs 1964, Binney et al. 1991, Blitz & Spergel 1991, Blitz 1993, Sellwood 1993, Stanek et al. 1994, and references therein).

Following KP we adopt the same power law mass function for the bulge and for the disk stars, with the number density proportional to $M^{-2}$, i.e. equal amount of mass per logarithmic mass interval.

We consider a conventional scenario first. We adopt the mass density in ordinary stars near the sun to be $\rho_0 = 0.05\ M_\odot\ pc^{-3}$ (Bahcall & Soneira 1980), with the mass range from $0.1 M_\odot$ to $1 M_\odot$, and a constant number density all the way to the galactic bulge, i.e. $d_{max} = 8\ kpc$. We adopt the theoretical distribution of microlensing event rate as a function of event time scale $\Gamma(t_0)$ given by KP and combine it with the OGLE efficiency for event detection $\epsilon(t_0)$ as given by Udalski et al. (1994b)[1], to obtain the cumulative number of events with the duration less than $t_0$:

$$N(\leq t_0) = \int_0^{t_0} \Gamma(t_0)\epsilon(t_0)\ dt_0 \quad . \tag{2}$$

The total number of events with $t_0 \leq 100$ days expected in this model is 2.2, four times less than observed.

Now we modify our model by increasing the local disk density by a factor of 3 to $\rho_0 = 0.15\ M_\odot\ pc^{-3}$, i.e. somewhat in excess of the estimate of the total local disk mass by Bahcall & Soneira (1980), the estimate considered too high by many recent investigations (Kuijken & Gilmore 1991, and references therein). In order not to be in direct conflict with what is observed near the sun we extend the range of lens masses into the brown dwarf region, i.e. we adopt a mass function extending over two decades: $0.01 \leq M/M_\odot \leq 1.0$. With the adopted power law there is just as much mass in objects below $0.1\ M_\odot$ (brown dwarfs) as in objects above $0.1\ M_\odot$ (stars). The model predicts 4.2 events, still a factor two short of the OGLE 9.

We may also consider just the optical depth to microlensing. The galactic bulge microlensing model of KP contributes only $0.5 \times 10^{-6}$ to the overall optical depth to gravitational microlensing, the halo contributes only $0.13 \times 10^{-6}$ (Griest et al. 1991), leaving $\tau_{disk} = 2.7 \times 10^{-6}$ to the disk if the total is to agree with the OGLE result. A simple formula relates the disk optical depth to the local disk mass density (cf. eq. 1 of KP):

$$\tau_{disk} = 6.5 \times 10^{-6}(3x^2 - 2x^3)\left(\frac{\rho_0}{1\ M_\odot\ pc^{-3}}\right) \quad , \qquad x \equiv d_{max}/R_0 \ , \tag{3}$$

where all symbols have the same meaning as in eq. (1). Adopting $\tau_{disk} = 2.7 \times 10^{-6}$ implies that $\rho_0 = 0.415\ M_\odot\ pc^{-3}$ for the "full" disk model ($x = 1$), and $\rho_0 = 0.83\ M_\odot\ pc^{-3}$ for

[1] The OGLE efficiency averaged over the 1992 and 1993 observing seasons was 0.0015, 0.029, 0.11, 0.22, 0.26 for $t_0 = 1.0$, 3.2, 10.0, 31.6, and 100.0 days, respectively.

the "hollow" disk model ($x = 0.5$). These densities are a factor of 3 or 6 higher than the highest dynamical estimate (Kuijken & Gilmore 1991; Bahcall, Flynn & Gould 1992). This discrepancy firmly rules out the disk as the main site of OGLE lenses.

Nevertheless, it is interesting to ask a question: what would be the lens masses if they were in a super-dense disk? It is very tempting to do the exercise, as OGLE provides the first information about the distribution of event time scales, $t_0$. We adopt the following procedure, which may be used for any model of the lens distribution. We take the rate of events as a function of event time scale $\Gamma(t_0)$ from the model. We take the efficiency of lens detection $\epsilon(t_0)$ from the experiment. We calculate the expected probability that an observed event should have a duration less than $t_0$:

$$P(\leq t_0) = \left( \int_0^{t_0} \Gamma(t_0)\epsilon(t_0) \ dt_0 \right) \left( \int_0^{\infty} \Gamma(t_0)\epsilon(t_0) \ dt_0 \right)^{-1} . \tag{4}$$

If the model is correct we expect the values of integral probability $P_k$ for all events to be uniformly but randomly distributed in the interval (0,1).

We adopted a "full" disk model ($d_{max} = 8 \ kpc$) with all lenses having the same mass $M$. We varied $M$ in small logarithmic steps over a large range, and we calculated the probability $P_k$ for all nine OGLE lenses for all the models. The distribution of those is shown in Fig. 2 for $-1 \leq \log \ (M/M_{\odot}) \leq 1$. The small points indicate values of $P_k$ for the nine OGLE lenses. They cluster near $P = 0$ if the lenses are massive and near $P = 1$ if the lenses are light. For a random but uniform distribution we require $\langle P \rangle = 0.5$. This is achieved for the lens mass $M/M_{\odot} = 0.65$, which is a typical stellar mass. Such objects would be very difficult to hide. Therefore, even if the dynamical mass estimates for the local disk density (cf. Kuijken & Gilmore 1991; Bahcall, Flynn & Gould 1992) were wrong for some obscure reason, we would be still faced with the problem how to make the numerous $0.65 \ M_{\odot}$ objects escape the detection in the local disk.

One might claim that perhaps what we know about the local disk does not apply to the disk half way between us and the bulge. For example, if the radial scale length is as short as 2.5 *kpc* then the radial increase in the density of stars would outweigh the decrease of density due to our line of sight getting out of the plane. Or the disk could be thicker some distance towards the galactic center. However, there is no observational evidence to support such hypothetical claims, and in fact the observational evidence is to the contrary: the *observed* number density of stars along the line of sight through Baade's Window appears to be uniform between the sun and $d_{max} \approx 3 - 4 \ kpc$, and it declines dramatically beyond $d_{max}$ (Paczyński et al. 1994).

## 3. DISCUSSION

In the previous section we have demonstrated that the rate of OGLE events cannot be explained by any reasonable galactic disk model. The rate cannot be explained by the only available galactic bulge model either. So, what is going on? We can only speculate at this time, but we think that a good case can be made for the lenses to be in the galactic bar, i.e. highly non-axially symmetric galactic bulge. There was evidence for the presence of a bar in the inner galaxy for about three decades (de Vaucouleurs 1964), but only recently it became popular (cf. Blitz 1993 and references therein). It is most clearly seen in the distribution of disk globular clusters projected onto the galactic plane, as shown in Fig. 5 of Blitz (1993). The bar seems to have its long axis inclined by $\sim 15^o$ to our line of sight. This orientation of the bar was also deduced by Binney et al. (1991) using the information about the observed gas velocities. The presence of the bar is clearly detected with the OGLE data as a difference of $\sim 0.37$ $mag$ in the apparent magnitude of the "red clump" stars in the two opposite OGLE galactic bar fields (Stanek et al. 1994).

The radial depth of the bulge/bar, $\Delta d_b$, is much smaller than its distance $d_b \approx 8$ $kpc$, hence its optical depth to microlensing scales as $\tau_b \sim \Sigma_b \Delta d_b$, where $\Sigma_b$ is the column mass density of the bulge/bar (cf. eq. 2 of KP). In the KP model the bulge was assumed to be axisymmetric, with $\Delta d_b \approx d_b \Delta\varphi_b$, where $\Delta\varphi_b$ is the apparent angular extent of the bulge/bar. If the bar axis ratio is large, i.e. if $f \equiv \Delta d_b/(d_b \Delta\varphi_b) \gg 1$, then its optical depth is increased by the factor $f$, and even more if its column mass density $\Sigma_b$ is increased.

There is another very important consequence of the bar-like shape of the galactic bulge: the average distance between the lens and the source is larger in a bar and hence the Einstein ring radius $R_E$ is larger. In a bar we expect $R_E$ to increase in comparison with the KP model, leading to the increase of $t_0$ for lenses of the same mass. For a given time scale $t_0$ the lens mass scales as $M_{lens} \sim 1/\Delta d_b \sim 1/f$, i.e. as the inverse of the bar axis ratio.

Unfortunately, the bar axis ratio $f$ is not well constrained either by data or by models at this time, but the radial extent of the bar may be much larger than its apparent transverse extent. If that is the case, i.e. if $f \gg 1$, then the KP optical depth is increased by the factor $f$, and the inferred masses are reduced by the same factor $f$.

It is worth noticing that the bulge or bar mass estimates by Kent (1992) and by Binney et al. (1991) were based on the dynamics, not on the observed light, i.e. they refer to the *total* mass, luminous and dark. The bar mass as deduced by Binney et al. (1991) was somewhat larger than the bulge mass estimated by Kent (1992) in his axially symmetric model. This also increases a bit the optical depth of a bar as compared to a bulge.

Had we blindly used the KP model and followed the procedure described in the previous section and displayed in Fig. 2, we would find the masses of bulge lenses to be $\sim 1.1\ M_\odot$. In a bar with the axis ratio $f \gg 1$ the corresponding lens mass would be reduced by the factor $f$. In any case, there is no need at this time to seek help of the low mass objects (brown dwarf) for the lensing as the problem is just the opposite: the observed time scales are too long.

There may be yet another effect which may affect the estimate of the lens masses. Stellar orbits within a bar are highly elongated, and the radial velocity dispersion (which is observed) may be much larger than the velocity dispersion transverse to the line of sight, as claimed by Binney et al. (1991). It is the transverse velocity $V$ that is relevant for lensing, and the reduction of $V$ leads to the increase of the time scale $t_0$. Unfortunately, the situation is somewhat confusing as Binney's et al. (1991) expectation does not seem to be supported by the data (Spaenhauer et al. 1992), and by the other bar models (Sellwood 1993, Zhao et al. 1994), which all seem to be consistent with the isotropic velocity dispersion.

The apparent excess in the observed number of microlensing events as expressed in terms of the optical depth to microlensing: $(3.3 \pm 1.2) \times 10^{-6}$ (Udalski et al. 1994b) is only a lower limit, as the OGLE project was not sensitive to events shorter than $\sim 5$ days or longer than $\sim 100$ days. The optical depth due to bulge lenses of *all* masses is only $\sim 0.5 \times 10^{-6}$ in the axially symmetric KP model, and any reasonable disk model contributes no more than that. It is virtually certain that the disk and the bulge are both important contributors to the observed microlensing. Their relative contribution has to be established observationally. What is needed is a map of optical depth to gravitational microlensing as a function of galactic coordinates. This will take a lot of observing and a lot of data processing, but the technology has been proven to work, i.e. the task is feasible. The disk contribution is expected to be fairly constant for $|l| \leq 20^o$, while the bulge contribution should be greatly reduced at $|l| \geq 10^o$ as compared to $l \approx 0^o$ (KP, Evans 1994). It is also very important to establish the radial depth of the bulge/bar observationally, in order to have as direct as possible determination of the axis ratio.

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Beginning with the 1994 season the OGLE project is capable of near real time data processing (Paczyński 1994). The new computer system automatically signals the events while they are on the rise, making it possible to carry out photometric and/or spectroscopic follow-up observations. The observers who would like to be notified about the on-going events should send their request to A. Udalski (udalski@sirius.astrouw.edu.pl).

The photometry of the OGLE microlensing events, their finding charts, as well as a regularly updated OGLE status report, including more information about the

"early warning system", can be found over Internet from "sirius.astrouw.edu.pl" host (148.81.8.1), using the "anonymous ftp" service (directory "ogle", files "README", "ogle.status", "early.warning"). The file "ogle.status" contains the latest news and references to all OGLE related papers, and the PostScript files of some publications, including Udalski et al. (1994b). The OGLE results are also available over "World Wide Web": "http://www.astrouw.edu.pl/".

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## FIGURE CAPTIONS

Fig. 1.— The location of the 9 OGLE lensing events (large circles) are shown in the color – magnitude diagram for Baade's Window and the galactic bar fields combined. Only $\sim 5\%$ of all OGLE stars are shown. The dashed line shows the limit of lenses detectability given by the condition $I < 19.5$.

Fig. 2.— The distribution of $P_k(\leq t_0)$ values is shown with the dots for all 9 OGLE lensing events for a series of models with various values of the lens masses, $\log M$, with all lenses having the same mass in a given model. The average value of the probability $\langle P \rangle$ is shown for every model with a filled triangle. For the correct model the values of $P_k$ should be randomly distributed in the interval (0,1), and it should have $\langle P \rangle = 0.5$. This model is shown with a dashed horizontal line corresponding to $M/M_\odot = 0.65$. The "full disk" with $\rho_0 = 0.415\ M_\odot\ pc^{-3}$ plus the KP bulge contributed to the lensing.